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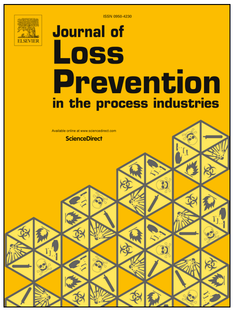

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Development of a Techno-Economic Framework for Life Extension Decision Making of Safety Critical Installations

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Abstract

One of the major decisions in management of the industrial assets is to ensure the feasibility of life extension process for safety critical components when they reach end-of-life. Most of the existing life extension decision-making models are restricted solely to either "technical" or "economic" feasibility analyses that may lead to inaccurate results or incorrect conclusions. In this paper, a comprehensive life extension feasibility assessment framewok by taking into account both the technical and economic considerations is developed. The proposed techno-economic model for life extension of safety critical elements consists of three phases: preparation, assessment, and implementation. The technical assessment part of the framework incorporates all aspects of data collection and review, screening and prioritization of safety critical elements, condition assessment, estimation of remaining useful life, and risk analysis, while the economic assessment part deals with cost-benefit analysis. The decision to qualify a safety critical element for continuous operation beyond its service life is made based on a "life extension measure (LEM)" which is calculated by combining two indexes of "equipment health condition" and "economic added-value" obtained respectively from the technical and economic assessments. The model is applied to support the life extension decision-making procedure for water deluge systems in offshore oil installations. The results of the study show that the model is highly capable of assisting asset owners to evaluate the technical and economic benefits of extending the service life of components.

Keywords

Safety Critical Element (SCE), Life Extension (LE), Reliability, Techno-Economic Analysis, Maintenance, Offshore Oil and Gas.

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Nomenclature

A_D	equipment's damage area
A_{ED}	environment's damage area
AFMEA	ageing failure mode effect analysis
ALRC	asset loss risk cost
BCR	benefit cost ratio
C_A	asset loss cost per unit area
CBA	cost-benefit analysis
C_{ED}	cost of environmental damage per unit area
C_H	health-care cost associated with a fatality
C_P	production rate per day
C_{SC}	surface clean-up cost
EDRC	environmental damage risk cost
EHI	equipment health index
HHLRC	human health loss risk cost
LE	life extension
N_D	number of people affected by a fatality
NPV	net present value
PLRC	production loss risk cost
RPN	risk priority number
RUL	remaining useful life
SCE	safety critical element
T_d	expected downtime
TRC	total risk-cost

1. Introduction

The increasing demand in world's energy consumption has made life extension (LE) a necessary part of economic life of nuclear power plants, electrical power infrastructures, renewable energy structures and offshore oil and gas assets. More than half of the North Sea's oil and gas installations have exceeded their original design life and now require upgrade, repair, and/or replacement (Stacey, 2011). The lifespan of a number of nuclear reactors in the United States, United Kingdom and France has been extended by twenty years, from 40 to 60 years of life (http://www.eia.gov).

Today's infrastructures are composed of many complex, interacting subsystems and components which usually include Safety Critical Elements (SCEs). Even though extending the life of industrial assets can result in economic added-value over the long term, the condition of some SCEs may not be suitable for extended operations from safety or environmental perspectives. Thus, the need for development of an appropriate LE management framework for SCEs is increasingly becoming critical. According to Matteson (2014), establishing such a framework can be very useful to assist companies and regulatory authorities in ensuring continued operation of installations beyond original design life.

For a successful implementation of the LE management process, a multi-disciplinary decision-making methodology is required to develop (Vaidya and Rausand, 2011). This is because achieving an efficient LE solution requires inputs from all stakeholders, including designers, system engineers, manufacturers, material specialists, operators and maintenance technicians, health and safety professionals, financial and economic analysts, and human factor researchers. Therefore, the LE management process must be defined taking into account not only economic factors such as maintenance expenditures but also technical requirements such as availability and survivability of SCEs during extended period of operation. Adhikary and Kundu (2014) suggested that LE feasibility studies should be based on techno-economic factors, providing the best solution to asset managers. However, many of the existing decision-making models are restricted solely to either “technical” or “economic” considerations. Galbraith *et al.* (2005) developed a capability maturing model (CMM) to assess the technical qualification of offshore oil installations for LE. A safety report published by the International Atomic Energy Agency (IAEA) (2008) provides a framework for addressing technical challenges associated with long-term operation of structures, systems and components in nuclear power plants. Hokstad *et al*. (2010) proposed a framework for LE process, integrating material degradation, obsolescence and organisational issues to ensure acceptable technical integrity of offshore assets throughout their life extension period. Vaidya and Rausand (2011) proposed a model for technical health assessment of critical assets for LE and applied it to a subsea raw seawater injection system. Liu *et al.* (2014) presented a framework for managing LE of offshore oil and gas installations in Chaina’s Bohai Bay field. The framework mainly focuses on technical assessment of safety related systems for extended operations. Recently, Ramírez and Utne (2014) proposed a dynamic Bayesian network for assessing the LE of ageing repairable systems.

In spite of availability of the above-noted useful, important and advantageous frameworks, there are still some obstacles to the assessment of performance of LE process for SCEs. For instance, solutions derived from the available LE decision making models are heavily skewed towards only one criterion (e.g., cost, safety, integrity) that may lead to inaccurate results or incorrect conclusions for asset managers. Another drawback is that the existing frameworks are one industry-specific and may therefore lack applicability outside the industry from which they were originated.

The current paper aims to address the above-mentioned drawbacks of the existing LE decision models. A comprehensive and generic techno-economic framework is proposed using the asset condition assessment and cost-benefit-analysis (CBA) techniques to evaluate the qualification of SCEs for LE. The decision to qualify a SCE for continuous operation beyond its service life is made based on a "life extension measure (LEM)" which is calculated by combining equipment health index (EHI) and economic index (EI) obtained respectively from the technical and economic assessments. The proposed approach is validated with a case study of a water deluge system in offshore oil installations and the results are subsequently discussed and evaluated. The generic nature of the proposed framework makes it applicable to various other engineering systems such as renewable and fossil-fuel technologies, railway infrastructures, aerospace structures, automotive machineries, etc.

The rest of the paper is organized as follows. Section 2 presents the techno-economic LE management framework. In Section 3, the model is applied to a case study and the results are analyzed in Section 4. Finally, the research is concluded in Section 5.

2. The Proposed framework

In this Section, a conceptual framework is developed for the purpose of determining the efficiency of LE decisions for SCEs. Most of the information used to produce this framework comes from two sources – face-to-face semi-structured interviews with experts who are actively involved in undertaking LE projects, and published literature in nuclear power, offshore oil and gas, petrochemical, renewable energy, rail transport, aviation, shipping, and electricity distribution and transmission sectors. As shown in Figure 1, the proposed framework for LE decision-making contains three phases: 1) preparation, 2) assessment, and 3) implementation. The key tasks in each of the three phases are described in the following sub-sections.

1.1. Phase 1: Preparation

The first phase in the LE management process is the preparation stage which includes three tasks of defining the premises for LE, data collection, and screening and prioritisation of SCEs.

2.1.1 Definition of premises for LE

The LE management process begins with clearly stating the objectives of undertaking such a programme, where these objectives must fit into stakeholders' requirements for the extended operation of assets. Stakeholders for a LE project include regulators, government agencies, asset operators and investors. Regulators are often appointed by governments in many jurisdictions to regulate operators' activities and procedures through laws. Non-compliance to these regulations can result in significant penalties and fines or even invalidation of operational license. Operators and investors also need equipment and installations remain fit-for-purpose throughout their extended lives to maximise return on investment (ROI). In most of industries, the main objective for LE is to increase the level of production and, thus, the revenue performance. However, upgrade and modernisation of structures, systems and components to maintain high level of integrity and safety standards can be another rationale for LE.

Figure 1

2.1.2 Data collection

The operational integrity of a system for LE depends on how it has been designed, constructed, commissioned, operated and maintained over the original lifetime. Lack of high-quality data can strongly affect the results of LE decision models and procedures. According to Hokstad *et al.* (2010), in order to assess accurately the feasibility of a LE program it is necessary to collect data during the design, commissioning, operation, maintenance and modification phases. Therefore, appropriate mechanisms should be established to enhance the capabilities of data collection platforms in capital intensive engineering industries and maintain the integrity of assets during extended life of operation. Based on the literature review conducted as a part of this research, a list of data elements for LE decision making process were identified and validated by the expert panel (composed of original equipment manufacturer (OEM), asset managers, operators, inspectors, safety executives, etc.). Table 1 summarizes various types of data required for (or produced by) an effective LE assessment of SCEs.

Table 1

2.1.3 Screening and prioritization of SCEs

In this task, the SCEs of an installation asset are systematically identified and prioritized according to specific criteria. It might be costly or time consuming to perform LE upgrades on all systems and structures. The resources available for LE — finance, manpower, materials and technology should mainly be allocated to the components whose failure could result in loss of life, significant property damage, damage to the environment, or long downtimes. Figure 2 illustrates a flow process diagram for the task of screening and prioritization of SCEs for further detailed analysis. The main objective of screening SCEs is to focus limited LE management resources on those systems and components whose functions are more critical to safety. In addition, the prioritization of SCEs can substantially improve the reliability and productivity of equipment and processes.

Figure 2

Several analytical tools have so far been used to screen and prioritize the SCEs. Cause-Consequence Analysis (CCA), checklist analysis, Event Tree Analysis (ETA), Fault Tree Analysis (FTA), HAZard and OPerability analysis (HAZOP), Failure Mode and Effects Analysis (FMEA), Failure Mode, Effects and Criticality Analysis (FMECA), and what-if analysis are some of the most common available tools.

This study uses a modified FMEA tool, called Ageing Failure Mode and Effects Analysis (AFMEA) (Nitoi *et al.*, 2011) for ranking and prioritising the SCEs. The Risk Priority Number (RPN) for potential ageing-related failure modes are evaluated using 10-point rating scales for severity of impact (S), likelihood of occurrence (O) and likelihood of detection (D) which are tabulated in Tables (2)–(4). AFMEA is a technique which has been applied in the nuclear energy industry to investigate the ageing effects on critical systems' vulnerabilities. In this paper, we apply the AFMEA technique to identify systems and components possessing high degradation rates. One of the main strengths of this approach is that it allows conducting qualitative and quantitative analyses to evaluate the contribution of SCEs to overall risk of failures in an installation or a system. It is also a structured, sequential and repeatable technique which can be performed using the following steps:

- Breaking the system down into sub-systems.
- Identifying the sub-systems functions.
- Understanding the stress factors for each sub-system and determining possible ageing failure modes.
- Specify detection methods for each possible ageing failure mode.

- Evaluating the risk of each ageing failure mode by assigning indices to S, O and D as presented in Tables (2)–(4).
- Calculating the RPN by multiplying severity, occurrence and detectability ratings, i.e., RPN = S×O×D.
- Ranking and prioritising the sub-systems according to their RPN values.
- Making corrective/preventive actions.

Table 2

Table 3

Table 4

The RPN is used to prioritise various failure modes caused by the ageing phenomenon. This number is a value between 1 and 1000, with 1 being the lowest ranking and 1000 the highest. The RPN value represents the effect or contribution of each ageing failure mode to the system's total risk. The assets based on their RPN values are classified into three groups: less sensitive to ageing, moderately sensitive to ageing, and highly sensitive to ageing. In this study, the sub-systems having RPN values less than 100 are grouped as less sensitive to ageing and therefore less critical. Sub-systems with RPN values between 100 and 200 are grouped as moderately critical because of their moderate ageing impacts on system safety. Lastly, the sub-systems with RPN values greater than 200 are classified as highly critical because such sub-systems are highly sensitive to ageing and will have a high degradation rate.

2.2 Phase 2: Technical and economic analysis of LE

The second phase of the proposed framework comprises two key modules: (i) technical assessment module which evaluates the equipment's health condition for LE and (ii) economic assessment module which examines the monetary added-value of LE. A techno-economic feasibility analysis framework for life extension of SCEs is proposed in Figure 3.

Figure 3

The two technical and economic assessment modules are explained in details as following:

2.2.1. Technical assessment module

The technical assessment module involves the application of condition assessment tools to determine current physical and functional health status of an asset. Risk assessment methodologies have widely been used for this purpose in some industries (e.g., see Palkar and Markeset, 2012; Liu *et al.*, 2014; Carvalho *et al.*, 2015). On the other hand, probabilistic safety assessment (PSA) models such as analytical unavailability and unreliability models have also been employed in the nuclear industry to determine current health status of safety related systems (e.g., see Martorell *et al.*, 1999; Kancev *et al.*, 2011; Kancev and Cepin, 2012; Martón *et al.* 2015). Prognostic Health Management (PHM) is also gaining prominence in condition assessment and predicting remaining useful life (RUL) of safety related systems. Ramuhalli *et al.* (2012) applied PHM techniques to assess and predict the RUL of nuclear reactor components. Our proposed framework adopts an assessment rating approach as in references Palkar and Markeset, 2012; Liu *et al.*, 2014 and Carvalho *et al.*, 2015. However, the approach utilized in this study is more quantitative and accounts for greater number of key factors in LE technical assessment. The steps involved in this approach are described as below:

Step 1: Select one of the SCE's sub-systems based on the screening and prioritization results.

Step 2: Identify condition assessment factors important to LE assessment of the chosen sub-system.

Step 3: Divide the condition assessment factors into *history* and *health* factors according to their contribution to total risk.

Step 4: Assign a score (between 1 and 4) to each condition assessment factor, as presented in Table 5, based on the available data and the knowledge and experience of field experts or assessment team.

Table 5

Step 5: Sum up the weighted scores for history and health factors to obtain the asset condition score given by Eq. (1):

$$\text{Condition score} = \sum_{i=1}^{n} S_i w_i \text{ ; where } \sum_{i=1}^{n} w_i = 1, \tag{1}$$

where n indicates the number of elements (parameters) taken into account in each factor, S_i represents the rating score of the ith element, and w_i is the relative importance (weight) of element i which is calculated using a pairwise comparison of elements. Eq. (1) is based on the Simple Additive Weighting (SAW) or Weighted Sum Method (WSM), which is considered the simplest and most used approach for scoring and prioritizing SCEs based on multiple attributes.

Step 6: Determine the Condition Index (CI) using Eq. (2) as below (Jahromi *et al.*, 2009)

$$\text{CI} = \alpha \times \text{history score} + (1-\alpha) \times \text{health score}, \quad 0<\alpha<1 \,, \tag{2}$$

where α and $1-\alpha$ represent the relative importance of history and health factores in relation to each other.

Step 7: Display the sub-system's health condition in three colors of green, yellow and red according to the value of condition indices (see Table 6).

Table 6

Step 8: Estimate the RUL when the health condition of a sub-system is displayed in yellow.

Technical justification of a sub-system for LE is represented by binary variables ('0' and '1'), where 0 indicates a poor condition and 1 implies a healthy condition. Those sub-systems whose health conditions are displayed in green color are qualified for LE from technical perspective and their RUL will not require to be estimated. Therefore, the equipment health index (EHI) for these sub-systems is assigned to be one. The red zone represents intolerable risk and those sub-systems that fall into this category are not technically qualified for LE and hence, their EHI is assigned zero value. If equipment's condition index falls in the yellow zone, which is a warning zone, some further safety and/or process control measures must be added before the sub-system can be considered for LE. In order to assign an EHI for sub-systems in the warning zone, the operator has to determine their RULs.

Literature on various methods for estimating the RUL of safety systems can be found in Jardine *et al.* (2006) and Galar *et al.* (2012). After estimating the RUL of sub-system, it is compared to the remaining field life (RFL). If the RUL is less than or equal to RFL, the EHI is assigned as the value one which implies that the sub-system can be qualified for LE from technical point of view.

Step 9: Repeat process for all sub-systems of the SCE.

2.2.2. Economic assessment module

Even though the technical qualification is key for ensuring safe and reliable operation of SCEs during LE period, the economic evaluation of the project must not be ignored. The economic assessment accounts for the total investment cost required for implementation of LE strategies. In order to evaluate the economic feasibility of LE programs, an economic index (EI) on the basis of cost-benefit-analysis (CBA) is presented. According to Mechler and Hochrainer-Stigler (2013), the CBA is an analytical tool that compares the cost of implementing an activity with its benefits. An activity is considered worthwhile if the sum of its benefits becomes greater than the sum of its costs or, identically, when the benefit/cost ratio is more than 1. So, in order to perform an economic analysis for LE projects, the decision-makers must first identify the associated benefits and costs. Based on the literature and expert input, we compiled a list of potential benefits and costs associated with LE management process. Table 7 summerizes the benefit and cost elements involved in LE execution.

Table 7

2.2.2.1. Benefits of LE

The benefits of extending the service life of SCEs usually include: increased production (B_1), improved safety (B_2) and delayed decommissioning cost (continued license to operate) (B_3). Increased production is achieved by the ability to reduce the equipment downtime (B_{1a}) through either improving the fault detection capability or reducing the maintenance lead times. Another benefit associated with LE is the increased revenue generation (B_{1b}), since an increase in the level of production leads to larger revenue streams (Tveit *et al.*, 2014).

Improved safety involves the benefits that industries can receive by reducing fatalities (B_{2a} and B_{2b}) as a result of implementing LE programme. However, these benefits are often non-monetary and it is difficult to quantify them (Brandt and Mohd Sarif, 2013). It is shown in many case studies that when assets reach the end-of-life stage (i.e., the third stage of the bathtub curve), they often experience an increasing failure rate. So, an appropriate LE strategy has the potential to reduce the equipment failure rate (B_{2c}). It is also an established fact that extending the service life of SCEs can save costs by delaying the decommissioning process, which is considered as an added-value to assets managers. For further information on the life extension benefits, the readers can refer to Agah and Abyaneh (2011).

2.2.2.2. Costs of LE

The costs associated with LE process include capital investment (C_1), installation cost (C_2) and operating expenses (C_3). The capital investment costs associated with LE consist of cost of acquiring new equipment (C_{1a}) and the cost of hardware and software upgrades for SCEs (C_{1b}, C_{1c}) to achieve an appreciable level of safety which is a requirement for license application. Installation of newly acquired equipment requires hiring and paying a number of laborers (C_{2a}). In addition, the installation of new equipment may require some facilities to be shut down for a period of time, resulting in production loss penalties (C_{2b}). Furthermore, a number of service boats must be used for transportation of LE personnel, equipment and consumables to and from installations, whose associated costs are represented by C_{2c}. Operating expenditure consists of all operating expenses including maintenance cost (C_{3a}), royalty cost (C_{3b}), logistical support cost (e.g. spare part cost) (C_{3c}) and statutory taxes for the extended operation (C_{3d}).

Finally, the economic index (EI) can be determined using Net Present Value (NPV) or Benefit-Cost-Ratio (BCR) techniques. These techniques are briefly summarized as below:

- *Net Present Value (NPV)*

NPV is defined as the difference between the present values of benefit cash flows and cost cash flows over a period of time (Shafiee *et al*., 2016). In order to compute the NPV of a LE strategy, the below equation is used:

$$\text{NPV} = \sum_{t=0}^{T} \frac{1}{(1+r)^t}[B(t) - C(t)], \tag{3}$$

where $B(t)$ and $C(t)$ represent respectively the total benefits and costs in a given year t, $r > 0$ is the discount rate and T is the time horizon of LE programme. So, the NPV associated with LE of a sub-system is calculated using Eq. (4) given by:

$$\text{NPV} = \sum_{j=1}^{3}\sum_{t=0}^{T} \frac{1}{(1+r)^t}[B_j(t) - C_j(t)], \tag{4}$$

where $B_1(t)$, $B_2(t)$ and $B_3(t)$ represent the LE benefits in term of, respectively, increased production, improved safety and delayed decommissioning, and $C_1(t)$, $C_2(t)$ and $C_3(t)$ represent the LE costs in term of, respectively, capital investment, installation and operation. If the NPV for a LE solution becomes non-negative (i.e., $\text{NPV} \geq 0$), then the EI is assigned to be one; otherwise, if $\text{NPV} < 0$, the index is assigned zero value.

- *Benefit-Cost Ratio (BCR)*

BCR is defined as the present value of all benefits divided by present value of all costs. Therefore,

$$\text{BCR} = \sum_{j=1}^{3}\sum_{t=0}^{T}\frac{B_j(t)}{(1+r)^t} \Bigg/ \sum_{j=1}^{3}\sum_{t=0}^{T}\frac{C_j(t)}{(1+r)^t}\,. \tag{5}$$

Now, if the BCR for a LE solution becomes greater than or equal to one (i.e., BCR $\geq$ 1), then the EI will be assigned a value of one; otherwise, if BCR < 1, the index is assigned zero value. ☐

The economic assessment module in the second phase of our proposed framework uses a risk-cost assessment approach to calculate the risks and costs associated with a LE programme. The total risk-cost (TRC) includes four types of risks/costs arising due to asset loss (ALRC), human health loss (HHLRC), environmental damage (EDRC), and production loss (PLRC). Therefore,

$$\text{TRC} = \text{ALRC} + \text{HHLRC} + \text{EDRC} + \text{PLRC}. \tag{6}$$

These four types of risks/costs are described below in details:

- *Asset loss risk-cost (ALRC)*

Asset loss risk-cost refers to the costs associated with loss of equipment function or damage to equipment as a result of ageing phenomenon. Ageing effects on SCEs may also lead to major accidents such as fire and explosion. ALRC can be calculated using Eq. (7) given by:

$$\text{ALRC} = \text{A}_\text{D} \times \text{C}_\text{A}\,, \tag{7}$$

where A_D represents the equipment's damage area and C_A is the asset loss cost per unit area.

- *Human health loss risk-cost (HHLRC)*

Human health loss risk-cost (also known as statistical cost of life) is calculated by the product of the number of people that may be affected (N_D) and the health care cost associated with each fatality (C_H). Thus,

$$\text{HHLRC} = \text{N}_\text{D} \times \text{C}_\text{H}\,. \tag{8}$$

There is always a difficulty in assigning monetary values to human fatalities. For this reason, the cost of human fatalities may introduce a degree of uncertainty into the cost calculations. Khan and Amyotte (2005) suggested that some indicators such as cost of rehabilitation, insurance and worker's compensation rate can be used instead.

- *Environmental damage risk-cost (EDRC)*

Environmental damage risk-cost includes cost of all kinds of damage to operating environment and surface cleaning charges, if required. Then,

$$EDRC = (A_{ED} \times C_{ED}) + Cc, \tag{9}$$

where A_{ED} represents environment damage area, C_{ED} is the cost of environmental damage per unit area, and C_{SC} represents the surface clean-up cost.

- *Production loss risk-cost (PLRC)*

Production loss risk-cost due to asset damage is calculated by the production rate per day (C_P) multiplied by expected downtime (T_d) in days. Then,

$$EDRC = C_P \times T_d \, . \tag{10}$$

Finally, the life extension measure (LEM) is calculated as a product of the equipment health vondition and economic add-value index, i.e.,

$$LEM = EHI \times EI \, . \tag{10}$$

If LEM equals one, the sub-system will be qualified for LE from both the technical and economic perspectives and can be included in the LE programme.

2.3 Phase 3: Approval and implementation

The third phase of the proposed framework focuses on regulatory approval process and implementation of measures to monitor the effectiveness of the LE management process.

2.3.1 Regulatory approval

LE programme must be supported by engineering and technical documentation for justification of continuous operation of SCEs beyond their original design life. The main purpose of regulatory consideration and approval is to thoroughly assess the documentation submitted by operators and ensure that SCEs can perform their intended functions during the extended life of operation in accordance with relevant regulations. Regulators are required to review and verify that LE programme is consistent with current regulations and industry-approved standards. In the case when a SCE is not qualified for LE at the approval stage, a recommendation is made whether or not to decommission the facilities.

2.3.2 Implementation

This task of the framework provides the main expected outputs from the proposed LE management programme enabling optimisation and continuous improvement of the testing, inspection and maintenance activities required during the extended life period. Figure 4 illustrates a process designed in this study to ensure that asset integrity is maintained throughout the lifecycle, understand how asset reliability may change over time, provide indication of ageing and obsolescence, and select appropriate actions to upgrade or restore the asset.

Figure 4

3. Application

In this Section, the proposed model is applied to support the LE decision-making process for a water deluge system in an offshore oil and gas platform. The offshore platform was commissioned in year 1990 for producing oil and natural gas from the West African region. The platform is a tanker based floating production and storage (FPSO) facility and its water deluge system is expected to operate for an extended length of time, up to seven years. The required data for this study was collected from company's databases and manufacturer's catalogues and if some information were not available, an independent expert elicitation was performed with the panel members.

The water deluge system on the platform has been designed and constructed according to ISO standards and guidelines as described in the company's engineering documents. The typical sub-systems of a water deluge system is illustrated in Figure 5, As shown, they include seawater (SW) lift pump and booster pump packages with diesel power direct-driven system. The diesel engine drive system was replaced by a new one 10 years ago. The water deluge system is independent of SW cooling system and according to the inspection of piping and instrument data (P&ID), it is also independent of all other systems on the platform. Other sub-systems include: fire and gas (F&G) logic, nozzles, detectors, firewater (FW) ring main, pipes, controls, instrumentation and valves used for various purposes. In Figure 5, the arrows illustrate the direction of the water flow. The seawater is pumped at a height of 80m by the lift pump. The water then flows through the booster pump to the FW ring main for distribution. In addition, 55m^3 water per hour is used for diesel engine cooling. The FW ring main is fitted with check valves to avoid back flow to the pumping system. FW ring main piping are situated outside of hazardous areas to use for multi-directional flow.

There is an F&G logic which is responsible for starting diesel engine and pumps as well as opening of deluge valves at the alarm from detectors. According to the information collected from design manuals, the water deluge system is constructed from materials such as Cu/Ni (90/10) alloy for pumps and diesel engine cooling system and galvanised carbon steel for the piping network.

Figure 5

4. Results and discussion

In this Section, the results of the application case are presented and discussed.

4.1 Phase 1

- *Premise for LE*

The objective of this study is to extend the life of water deluge system for future operations.

- *Data collection*

The information required for analysis was collected from design, operation and maintenance manuals as well as other internal documents.

- *Screening and prioritisation of SCEs*

With reference to Figure 2, the results of the screening and prioritisation process are presented in Table 8. AFMEA study revealed that the failure modes of each sub-system are mostly caused by ageing phenomenon. Based on the RPN values obtained from AFMEA, all sub-systems were ranked and prioritised for LE analysis. However, the assessments focused on sub-systems with RPN values greater than 200.

Table 8

4.2 Phase 2

- *Techno-economic assessment*

Current health status of sub-systems and economic implications of selected LE strategies were assessed. The results for the techno-economic assessment are presented in Table 9.

Table 9

Results of the technical assessment indicate that the F&G logic has CI value of 3.7, and hence, it is qualified for LE process from technical perspective. This means that the existing maintenance and ageing management programmes could still be applied to manage the F&G system deterioration during extended life operation. The economic assessment indicated that the NPV for LE of F&G logic is greater than zero and BCR > 1, hence an EI value of 1 is assigned.

The analysis for the diesel engine drive system produced a CI of 3.9 and a positive NPV value as well as a BCR value greater than one. Therefore, it is qualified to consider for for extended operations.

The CI for SW lift pump is evaluated as 3.3, implying that the condition of sub-system is in the warning zone (displayed in yellow color). The value of EHI is assigned to be 1, because the RUL of sub-system from available data is estimated to be four years which is less than the RFL of seven years. This indicates that the oil field has still this potential to be considered for LE interventions, e.g., remanufacturing, reconditioning, etc. On another side, the economic assessment shows an NPV of $7615.50 and a BCR value of 3.13 was obtained, meaning that LE for the SW lift pump will result in substantial economic benefits to asset operators.

Technical assessment of piping network produced a CI of 1.6, indicating that the sub-system is not technically qualified for extended operations. Moreover, its economic assessment produced a negative NPV and a BCR value less than one.

In overall, based on the LEM values given in Table 9, the F&G logic, SW pump and the diesel drive system can be considered for LE. Even though three (out of four) of critical sub-systems have LEM of value 1, the entire water deluge system cannot entirely be qualified for LE management programme because the LEM for the piping network is zero. Hence, the overall system is still considered unsafe for extended operations. For this reason, the asset managers must first implement corrective/preventive actions on the piping network sub-system so that extending its life becomes feasible from both technical and economic perspectives, then the LE programme for the whole system can be proceed.

4.3 Phase 3

Implementation of the third phase is done on the basis of process presented in Figure 4.

5. Conclusions

In this paper, a techno-economic feasibility assessment model was developed for life extension (LE) decision making of safety critical elements (SCEs). The proposed model provides a powerful decision-making tool for assessing and qualifying the SCEs for LE process on the basis of asset condition assessment and cost-benefit-analysis (CBA). For the purpose of clarity, the efficacy of the proposed model was shown through an application to a water deluge system in offshore oil installations. The results of the application case study demonstrated the validity of the proposed framework for LE process in the offshore oil and gas industry. This study also overcame the shortcomings of available LE decision-making models which are restricted solely to either technical or economic considerations. Our proposed model provides decision–makers the ability to incorporate simultaneously all the technical and economic issues when applying LE strategies to SCEs.

The proposed techno-economic LE assessment model will be applied in the future to critical structures operating in other industries. Determination of the most economic length of LE interval for safety related assets (in the case when they are qualified for LE process) can be another area of research. Since economic losses due to safety and environmental damages cannot be easily quantified, thus some uncertainties in the assessment of LE costs are expected. Appropriate tools can be developed in the future to reduce uncertainty involved in the risk cost model. Also, computerised systems and processes must be developed to ensure that good quality data is available for LE assessment.

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Table 1. Identification of various data items required for (or produced by) life extension assessment process

Type of data	Required information	Source of data
Design Data	System/component design criteria	Operator
	Design specifications of various components	Operator
	Design codes and standards	Operators and government
	Drawings and layouts	Operators
	Design life calculations	Operators
	As built documents	Operators
	Material specification	ASTME, API, NORSOK, etc. standard document
	Technical and engineering adjustment during installation	Operators
	Regulations	Government
	HSE Standards	Government
	Guidelines	Government
Operational Data	RAMS	Operator
	Modification	‘’
	Operational parameters (e.g. pressure, temperature, flowrate etc.)	‘’
	Conditioning monitoring information	‘’
	New standards and recommended practices	‘’
	Experience since design and installation	‘’
	New tools since design and installation	‘’
	Systems, subsystems and sub assembly	‘’
	Ageing degradation records	‘’
	Production levels	
Cost Data	Cost of modification	Operator
	Cost of operation & maintenance	Operator
	Regulatory cost	Government
	Taxes	Government
	Royalty cost	Government
	Revenue	Operator
	Market price of oil and gas	Market sources
Model Output	Future planned maintenance or modifications or ageing management programme	Life extension assessment
	Length of life extension period	‘’
	Future operational cost	‘’
	Health status of assets	‘’
	Remaining service life	‘’

Table 2. Ratings for severity of ageing failure modes (Nitoi *et al.*, 2011)

Scale	Description	Criteria
1	None	Be unnoticed and not affect the performance and safety of system
2	Very Minor	Be unnoticed; minor effect on system performance and safety
3	Minor	Cause a minor nuisance; can be overcome with no loss of function to system and compromise safety.
4	Very Low	Cause minor performance loss
5	Low	Cause a loss of performance likely to result in a complaint
6	Moderate	Result in partial malfunction
7	High	Cause extreme process and equipment dissatisfaction
8	Very High	Render the process and equipment unfit for use
9	Hazardous, with warning	Be illegal
10	Hazardous, without warning	Injures are life threaten

Table 3. Ratings for probability of occurrence of ageing failure modes (Nitoi *et al.*, 2011)

Scale	Description	Criteria
1	< 2 per million	Once every 6-100 years
2	< 3 per 10 million	Once every 3-6 years
3	< 6 per million	Once every 1-3 years
4	< 6 per 100,000	Once per year
5	< 1 per 10,000	Once every 6 months
6	< 0.03 %	Once every 3 months
7	< 1 %	Once per month
8	< 5 %	Once per week
9	< 30 %	Once every 3-4 days
10	> 30 %	More than once per day

Table 4. Ratings for detection of ageing failure modes (Nitoi *et al.*, 2011)

Scale	Description	Criteria
1	Almost Certain	Defect is obvious and can be kept from affecting process
2	Very High	All units are automatically inspected
3	High	Condition monitoring , with 100% inspection surrounding out-of-control units
4	Moderately High	Condition monitoring used, with an immediate reaction to out-of-control conditions
5	Moderate	Degradation monitored via condition monitoring systems and manually inspected
6	Low	Manual inspection with mistake-proofing modifications
7	Very Low	All units are manually inspected
8	Remote	Units are systematically sampled and inspected
9	Very Remote	Occasional units are checked for degradation
10	Almost Impossible	Failure caused by degradation is not detectable

Table 5. Rating scores for condition assessment factors

Rating	Score	Risk level	Condition
A	4	None	Normal
B	3	Low	Moderately normal
C	2	Moderate	Not normal
D	1	High	Worst

Table 6. Asset health condition based on condition index

CI	Asset health condition
[4.0 -3.5)	Green
[3.5 -3.0)	Yellow
[3.0 – 0.0)	Red

Table 7. Benefits (B) and Costs (C) associated with life extension

Benefits/costs	Elements
B_1. Increased production	B_{1a}. Reduced equipment downtime B_{1b}. Increased revenue
B_2. Improved safety	B_{2a}. Reduced injury to personnel B_{2b}. Reduced death rate B_{2c}. Reduced equipment failure rate
B_3. Delayed decommission cost	
C_1. Capital cost	C_{1a}. Cost of purchasing new equipment C_{1b}. Cost of hardware upgrading C_{1c}. Cost of software upgrading
C_2. Installation cost	C_{2a}. Labour cost C_{2b}. Downtime cost C_{2c}. Logistical support cost
C_3. Operating expenditure	C_{3a}. Maintenance cost C_{3b}. Royalty cost C_{3c}. Logistical support cost C_{3d}.Taxes

Table 8. Selected SCEs for life extension assessment and analysis

Safety critical element: Water Deluge System		
Sub-system	Risk level with respect to ageing	Number of sub-systems in SCE
SW pump	High	2
Piping	High	35
Diesel engine	Moderate	2
F&G logic	Moderate	1
Total		40

Table 9. Results of the techno-economic life extension assessment

SCE	CI	RUL	BCR	NPV	EHI	EI	LEM
		yrs.		$			
SW pump	3.3	4	3.13	7615.50	1	1	1
Pipings	1.6	-	0.60	-1406	0	0	0
Diesel engine	3.9	-	2.1	3120	1	1	1
F&G logic	3.7	-	2.34	4800.39	1	1	1

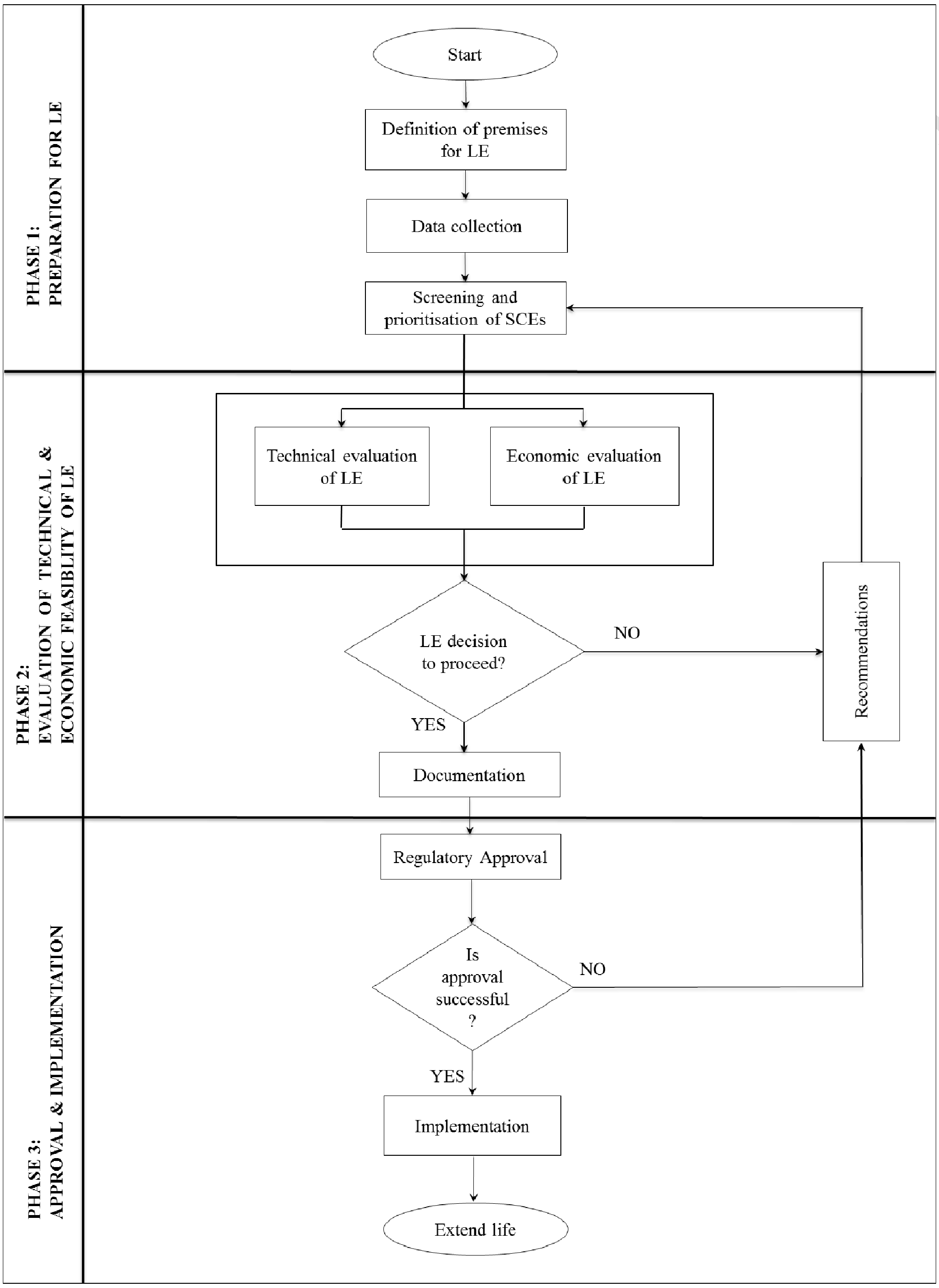

Figure 1. The proposed framework for life extension management of safety critical elements.

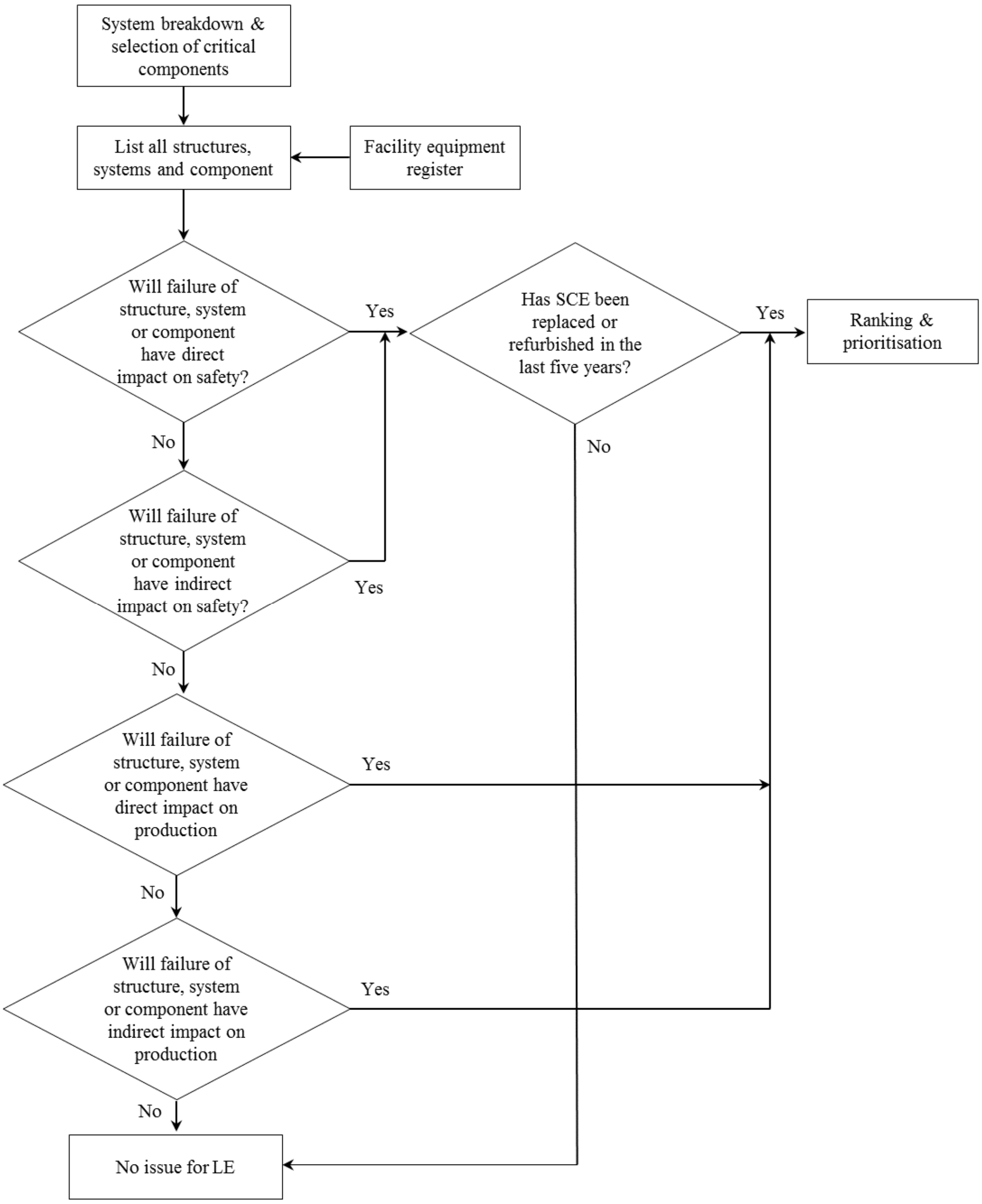

Figure 2. A flow process diagram for selection and prioritisation of safety critical elements.

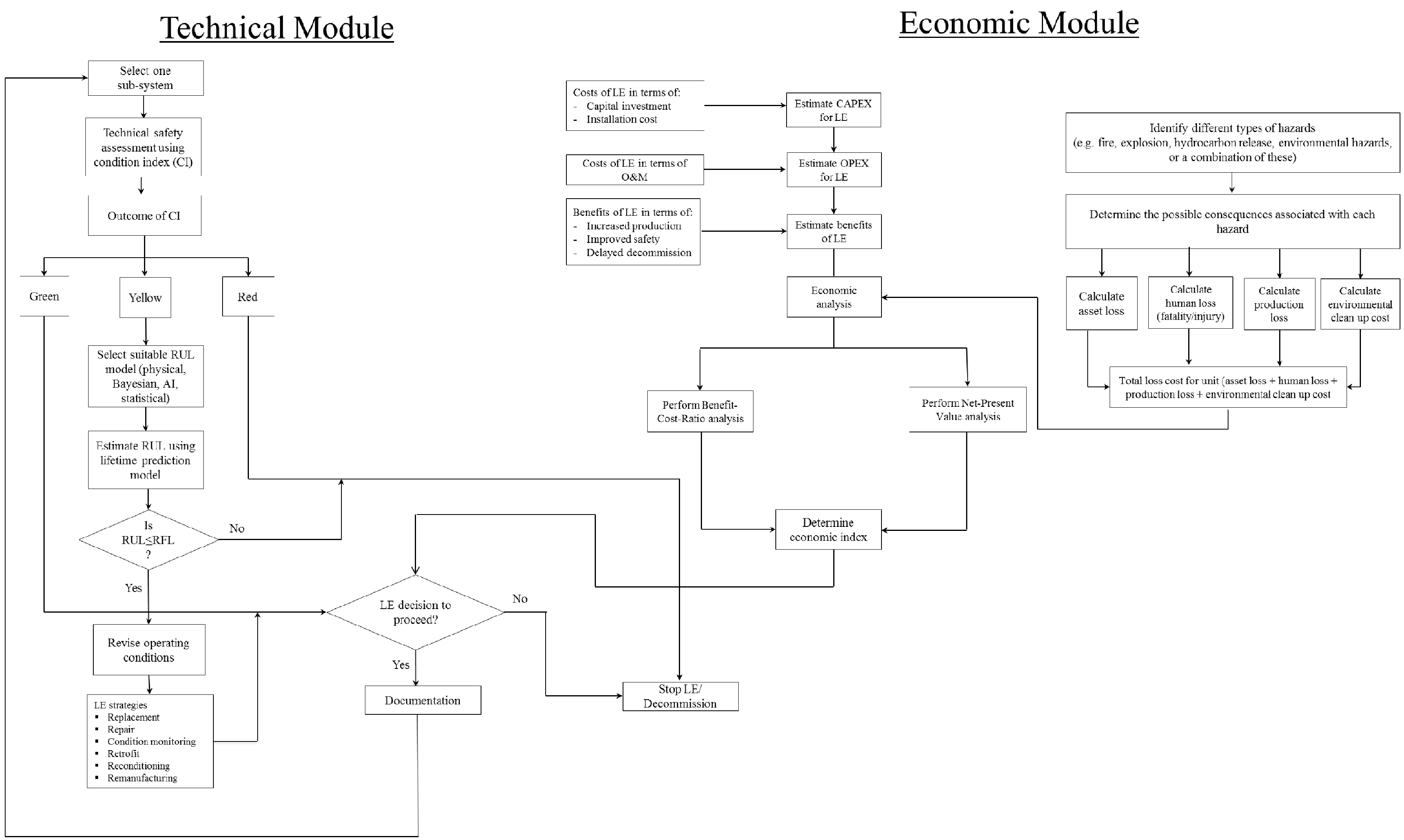

Figure 3. A techno-economic life extension feasibility analysis framework.

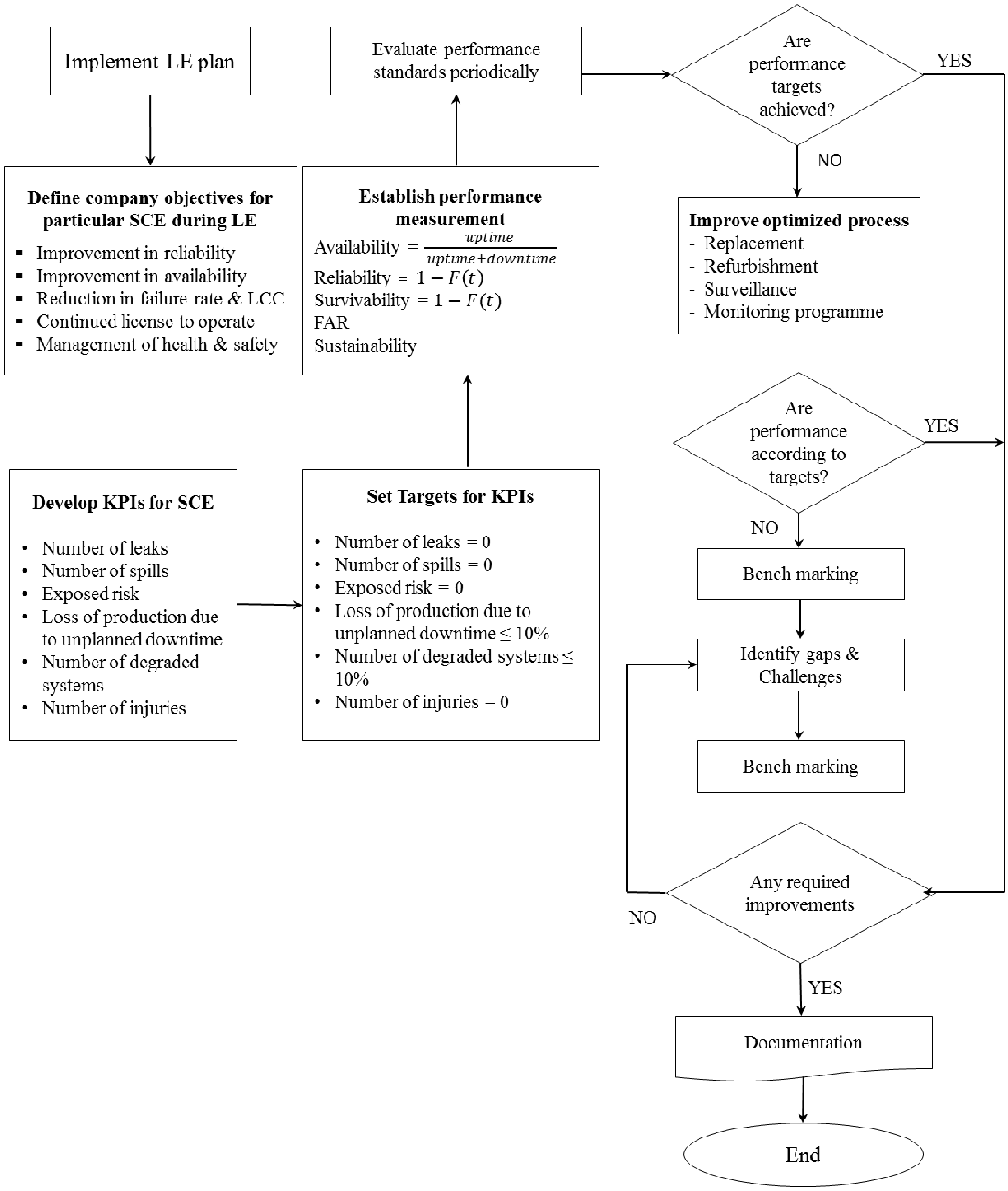

Figure 4. A flow diagram for life extension implementation.

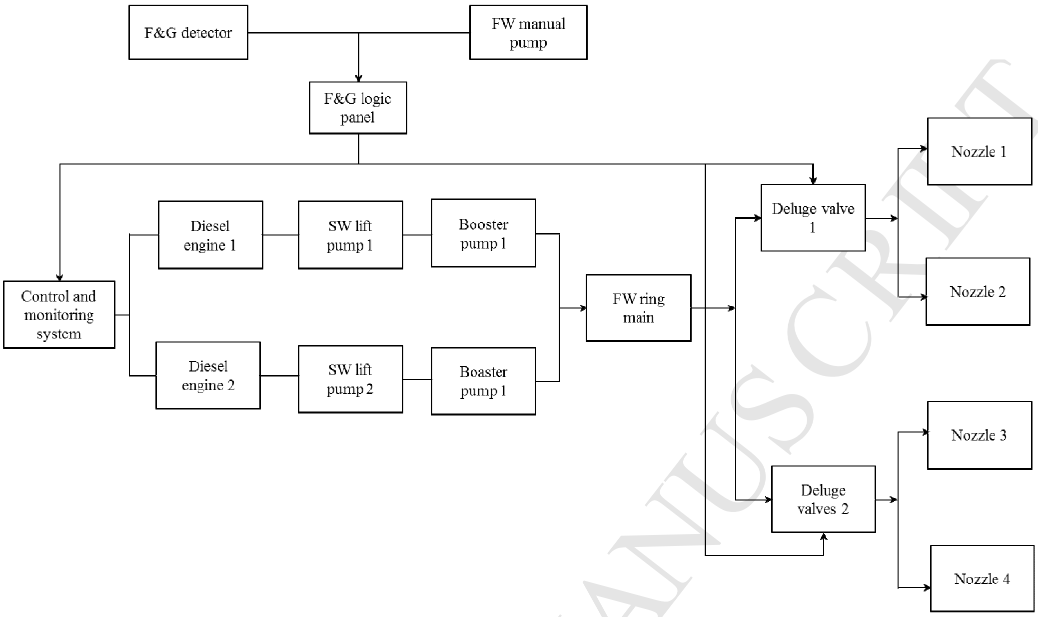

Figure 5. The sub-systems of a water deluge system.

RESEARCH HIGHLIGHTS

- A techno-economic model to evaluate the performance of life extension programmes for safety critical installations
- Incorporating equipment's condition assessment information into life extension decisions
- To apply a cost-benefit analysis (CBA) for life extension economic analysis
- Establishing a "life extension measure (LEM)" for life extension feasibility assessments
- To support life extension decision-making for a water deluge system on an offshore oil platform.